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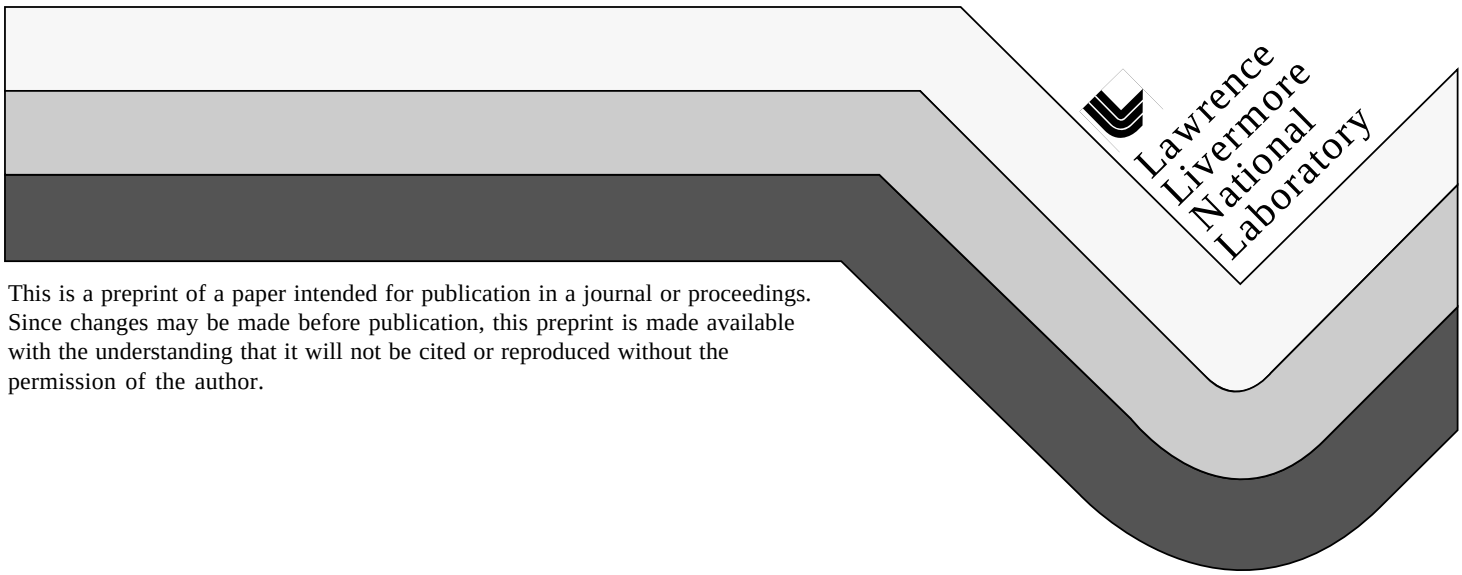

Photon Beam Description in PEREGRINE for Monte Carlo Dose Calculations

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The goal of the PEREGRINE Monte Carlo Dose Calculation Project [1] is to provide the capability for accurate and fast Monte Carlo calculation of radiation therapy dose distributions for routine clinical use and for research into the efficacy of improved dose calculation. To attain these goals, an accurate and efficient method of describing and sampling radiation sources is required. We provide a simple, flexible solution to that requirement. Our teletherapy source package for PEREGRINE—coupled with state-of-the-art Monte Carlo simulations of treatment heads—makes it possible to describe any teletherapy photon beam to the precision needed for highly accurate Monte Carlo dose calculations in complex clinical configurations that use standard patient modifiers such as collimator jaws, wedges, blocks and/or multi-leaf collimators. Generic beam descriptions for a class of treatment machines can readily be adjusted to yield dose calculation to match specific clinical sites.

This source package is simple and robust. It uses predefined descriptions of the fixed radiation field cast into the form of probability and fluence distributions. A single description paradigm characterizes direct and scattered components of the primary radiation field. The effects of all patient specific beam modifiers on the incident radiation are incorporated during the Monte Carlo dose calculation. All that is necessary to correctly calculate their effects is an accurate description of their geometry and composition. Output factors, wedge factors and off-axis ratios are all obtained without need for empirical corrections.

The distributions needed for dose calculations are derived from Monte Carlo simulations of bremsstrahlung generation of the radiation in the linac head using BEAM96 [2] and MCNP4b [3]. A related presentation [4] at this conference presents the details of the simulations and the different codes used. The results of those simulations are a set of individual histories—a history file—that represent a random sampling of the phase space of radiation generated in the linac head. To date, we have performed detailed simulations of clinical photon sources from the following linacs: Varian 600C (4 MV and 6 MV); Varian 2100C (6 MV, 15 MV and 18 MV); Siemens MD (6 MV and 15 MV); Siemens KD (6 MV and 18 MV). We are gathering information to include sources from other manufacturers. Our intent is expand our library of sources to include all relevant teletherapy photon sources. The source library will be available for use with PEREGRINE in research and clinical activities. As researchers and clinics begin to use PEREGRINE, we will add customized versions of the generic entries for each configuration.

Defining a Clinical Beam to PEREGRINE

Figure 1 shows a schematic diagram of the various components of a generic photon source description. To perform a dose calculation, PEREGRINE needs to know the following physical characteristics in the beam coordinate system for each Monte Carlo history to be tracked through the modifiers and patient mesh:

- (***x,y,z***) the starting coordinates;
- (***u,v,w***) the initial direction cosines with respect to (***x,y,z***) respectively;
- (***E***) the photon energy;
- (***W***) the relative sample weight (how many photons it represents).

To define a source for PEREGRINE, the phase-space history files are analyzed and separated into several different components. In general, we define one point (unscattered) component and one or more scattered components. The point component represents the

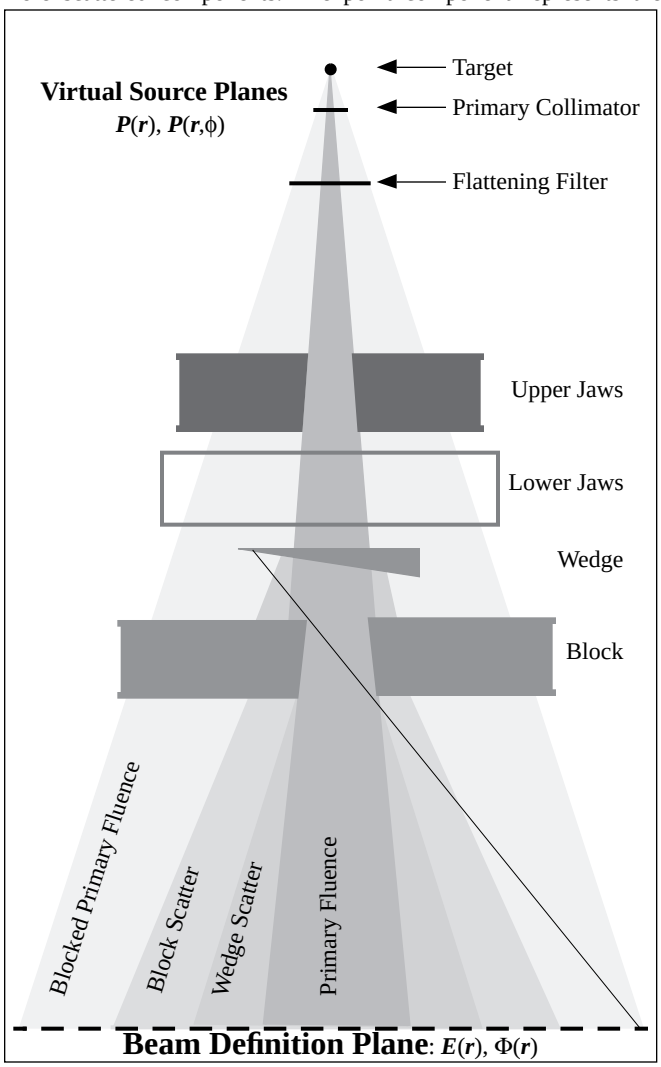

Figure 1: Schematic diagram of the PEREGRINE photon source representation.

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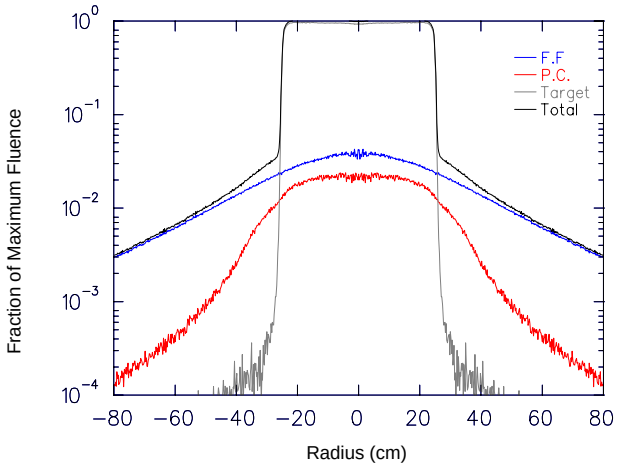

Figure 2: Radial distribution at gantry axis plane for direct, flattening filter and primary collimator subsources. Also shown is the total fluence.

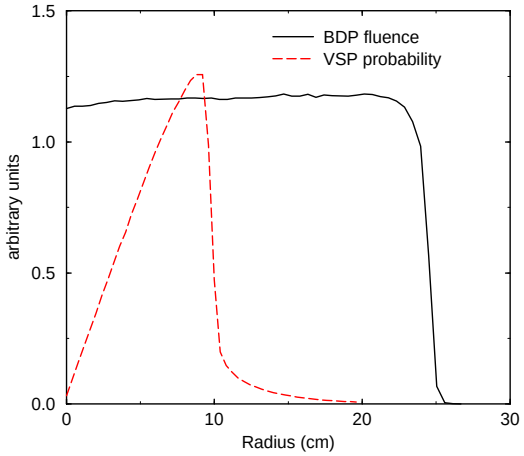

Figure 3: Beam definition plane and virtual source plane (radius scaled by 100×) spatial distributions for the point source component from a simulation of a 6-MV Varian Clinac 600C.

radiation coming from a small area within the bremsstrahlung target and backing that reaches the linac axis plane without further interactions in the linac head. The scattered components describe the effects of the primary (fixed) collimation, flattening filter, monitor chamber, etc. **Figure 2** shows the radial distributions on the beam-definition plane of a three-component description of a generic 6-MV Varian 2100C derived from a BEAM96 simulation.

The Beam Definition Plane

Each defined component has a *beam definition plane* (*BDP*) on which the relative energy fluence, $\Phi(\boldsymbol{r})$, and differential energy spectrum, $\boldsymbol{E}(\boldsymbol{r})$, are specified. The *BDP* is a plane perpendicular to the beam axis and is defined in the beam coordinate system. For clinical sources, we place the *BDP* at the isocenter of gantry rotation to ensure the best reproduction of the fluence and spectrum in the dose calculation volume. The distributions on the *BDP* are used to select the initial location ($\boldsymbol{x,y,z}$), energy ($\boldsymbol{E}$), and sample weight ($\boldsymbol{W}$).

Accelerator-based photon sources are tuned by the manufacturers using filters to generate a nearly flat energy fluence transverse to the beam at the nominal isocenter. This suggests that the quantity to preserve in defining the spatial distribution of histories is the simulated or measured energy fluence (MeV/cm^2) profile. Equation 1 is the formula used to generate a relative fluence function with an average value of 1 on the set of annuli defined by the points $\{\boldsymbol{R_i}\}$ with areas $\{\boldsymbol{A_j}\}$. Typically, we use 50 radial points to define the fluence function.

$$\Phi(\boldsymbol{R}_{j+1/2}) = \frac{\boldsymbol{A}_{total}}{\boldsymbol{A}_j \boldsymbol{E}_{total}} \sum_i \boldsymbol{E}_i \boldsymbol{W}_i ,$$

summed over the set $\{\boldsymbol{i} | \boldsymbol{R}_{j-1} < \boldsymbol{r}_i < \boldsymbol{R}_j\}$. (Eq. 1)

The energy spectrum, $\boldsymbol{E}(\boldsymbol{r})$, is specified on the *BDP* as a series of annular radial tiles. A different probability distribution in energy is created for each *BDP* tile boundary. The radial span of the *BDP* tiles matches the span of the *BDP* fluence function. A continuous energy spectrum in $\boldsymbol{r}$ is determined during the dose calculation by linear interpolation in area between the tile boundaries. This is accomplished by weighted selection from the boundary distributions with the weights determined by the current radius and the boundary radii. The energy spectrum varies smoothly over the radius of the linac spot size, so 8–10 tiles is usually sufficient for accurate reproduction of the spectrum.

The Virtual Source Plane

With the definition of a BDP, the method for defining the initial direction ($\boldsymbol{u,v,w}$) of histories remains to be specified. For each component, we define a *virtual source plane* (*VSP*) on which histories are taken to originate. Direction cosines are defined by the vector between the locations on the *BDP* and the *VSP*.

A point-source *VSP* is essentially a reproduction of the profile of the incident electron beam on the target with small tails due to scatter in the target and backing. The point *VSP* spatial distribution is determined by backtracking each history event to $\boldsymbol{z} = \boldsymbol{z}_{vsp}$. The value for $\boldsymbol{z}_{vsp}$ is chosen by finding the location that yields minimum spot size, usually very near, but slightly in front of the bremsstrahlung target. The backtracked events are used to generate a radial probability distribution (MeV/cm) using the generic form in Equation 2.

$$\boldsymbol{P}(\boldsymbol{X}_{j+1/2}) = \frac{1}{\boldsymbol{E}_{total}(\boldsymbol{X}_j - \boldsymbol{X}_{j-1})} \sum_i \boldsymbol{E}_i \boldsymbol{W}_i \qquad \text{(Eq. 2)}$$

This is in contrast to the photon fluence (MeV/cm^2) distribution on the *BDP* defined above. **Figure 3** shows the *VSP* radial distribution and the *BDP* fluence function for a 600C 6-MV source modeled with a 2-mm diameter electron beam spot size. For point components, correlation between location on the *BDP* and location on the *VSP* is ignored in defining the distributions and selecting the two points.

The scattered components have more angular structure and a higher degree of correlation between energy and direction. To handle this additional correlation, the definition of the *VSP* is extended to allow the use of an azimuthal distribution as well as a radial distribution. The scattered components—from the flattening filter, primary collimator, etc.—are reproduced to within a few percent of their contribution at axis by a separable function in $\boldsymbol{(r,\phi)}$.

Source Sampling

Besides accuracy in the description of the radiation field, efficiency (speed) is a critically important issue in delivering a practical Monte Carlo dose calculation. This component model is designed for efficient sampling. By defining the radiation fluence at the isocenter, the cropping effects of collimator jaws can be precalculated beam by beam at generation, eliminating the need to sample from large portions of the *BDP*. For example, on a 10×10 field, confining the sampling area for the point component to that area—plus a margin to account for the *VSP* spot size—eliminates ~92% of the *BDP* from consideration. The transmission through the body of the jaw is ignored (see below.) For scattered components, a larger margin is used, but a significant portion of the *BDP* can still be ignored.

To preserve energy balance between the components and weight balance between the individual histories, component selection is based on a probability distribution that includes the beam weights, component energy fractions, and the *BDP* sample fractions. The initial values for x and y are chosen uniformly in the remaining rectangle on the *BDP*.

Internal to PEREGRINE, the weight of a selected history is considered to be a molar weight, not a measure of the total energy of the history. With this definition of the *BDP* and the selection process for x and y, the molar weight of a history is given by

$$W = \frac{\Phi(r)}{\langle E(r) \rangle} \qquad \text{(Eq. 3)}$$

where $\langle E(r) \rangle$ is the average photon energy at $r(x,y)$. $\langle E(r) \rangle$ and $\Phi(r)$ are obtained by linear interpolation from tabulated values. The selection of energy and *VSP* location are done directly from the associated probability distributions.

Absolute Dose Calibration

Absolute dose is determined clinically by the conversion from monitor units (MU) to measured dose per MU. One prevalent standard is to calibrate the monitor chamber to deliver 1.0 cGy/MU at d_{max} on the central axis for a 10×10 open field. The beam normalization in PEREGRINE is based on total energy produced in the beam head before modifiers. PEREGRINE determines relative dose in the patient mesh by tracking individual photon histories. Photons are not explicitly tracked through the monitor, but instead are tallied to get the total sampled beam energy from all components. To obtain absolute dose for comparison to clinical measurements, a conversion between total beam energy and MU is required. This is done by calculating the dose in the calibration configuration and recording the necessary conversion factor between total beam energy and MU in the source description file.

Multiple Beam Normalization

PEREGRINE can calculate dose from multiple beam plans in a single calculation, if the weight (in MU) of each beam is specified in the plan. PEREGRINE maintains energy balance between the beams and components in the ratios given in the plan and source description by selecting histories from the beams at random, based on the partition of the total produced energy. The partitioning includes the MU for each beam, the MU factors in the source descriptions, and the component energy fractions in each source.

Clinical Site Adjustment

The most important aspect of source description is the ability to match measurements from, and therefore accurately calculate dose for, a given clinic. Since specific installations of similar linacs can have subtle differences in head construction and electron beam characteristics, as well as different modifier options and site calibrations methods, some site adjustment of the generic source description will be necessary for each installation.

To facilitate this adjustment, certain information about the installation site is required. Measurements of output factors, open field depth dose, open field profiles and wedge factors are necessary. A description of the monitor unit calibration configuration and convention is needed to determine the proper global normalization constant. Physical descriptions of modifier options, such as wedges and blocks, are also necessary. For wedges, we need the physical wedge profile, the material (alloy) and density of the wedge and tray, and the axial location of the wedge tray. For blocks, the block thickness, material and density, and the location of the block tray must be provided. Any other special modifiers must also be described if they are

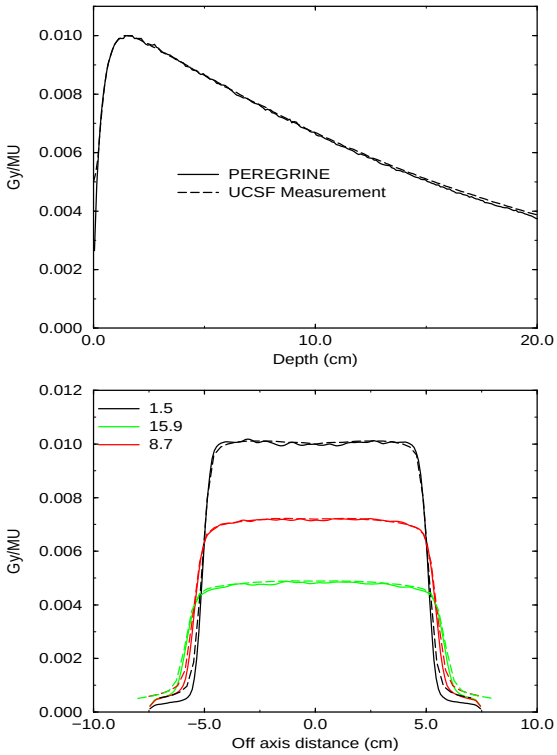

Figure 4: PEREGRINE vs. Measurement: Depth dose and profiles for a 10×10 open field for a 6-MV Varian 600C [6].

to be used in PEREGRINE calculations.

Given access to this data, a simple, few-parameter fit allows the adjustment of the generic machine description. Three typically used parameters are the maximum photon energy, the radial fluence of the point component, and the shape of the point-component virtual source.

Comparison to Measurements

The real measure of success of PEREGRINE's source model lies in comparison of dose calculations to clinical measurements. The PEREGRINE calculations shown here were run until the standard deviation of the mean dose at each point was less than 0.5% of the maximum dose in the mesh. The measured data are from the University of California, San Francisco [6] and the Medical College of Virginia [7].

Open Field Depth Dose and Profiles

Open fields have only collimator jaws as modifiers. PEREGRINE does not transmit through, or scatter photons from, the jaw material. A simple ray-tracing algorithm is used that terminates photon histories that contact any portion of the jaw set. The result of this simplification is an increase in efficiency and loss of fine detail in the tails of the penumbra. **Figure 4** shows the calculated and measured depth dose and profiles for a 10×10 open field for a 6-MV beam. **Figure 5** shows profiles at three depths calculated from the same beam phase space description for 2×2 and 30×30 fields.

Open-Field Output Factors

An essential factor in absolute dose calibration is field-size dependent output factors. **Figure 6** shows the level of agreement between measured output factors and calculated values. The effects of head scatter and lateral transport are handled in the dose calculation. These effects are the dominant cause the dose/MU to vary with field size. The neglect of jaw scatter does not significantly affect the central axis dose or the shape of the high-dose region of the profiles.

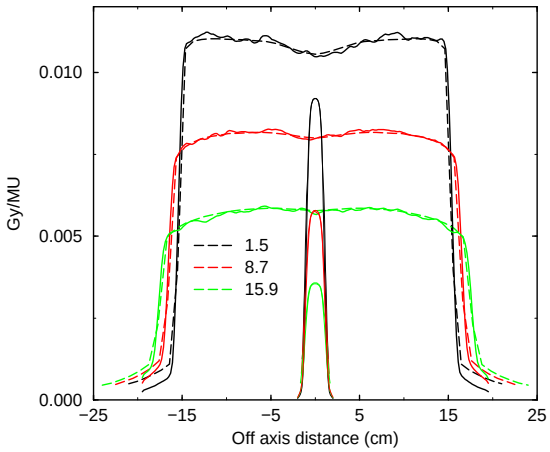

Figure 5: PEREGRINE vs. Measurement: 2×2 and 30×30 profiles at 1.5, 8.7 and 15.9-cm depths for 6-MV Varian 600C [6].

PEREGRINE makes no correction for backscatter into the monitor chamber.

Wedge Factors and Profiles

Most curative-intent treatment involves blocks, wedges or other modifiers, singly and in combination. Therefore, the effects of transmission and scatter off of these modifiers is much more important.

Transmission and scatter from wedges and blocks are handled with full photon-transport physics. Wedge factors and block attenuation are accurately reproduced, knowing only the geometry and composition of each modifier. The methods, accuracy and limitations of the techniques used for each modifier type are described in a related presentation at this conference [5]. The accuracy of the wedge transport algorithm is shown in the comparison of profile measurements to PERGRINE calculations in **Figure 7**.

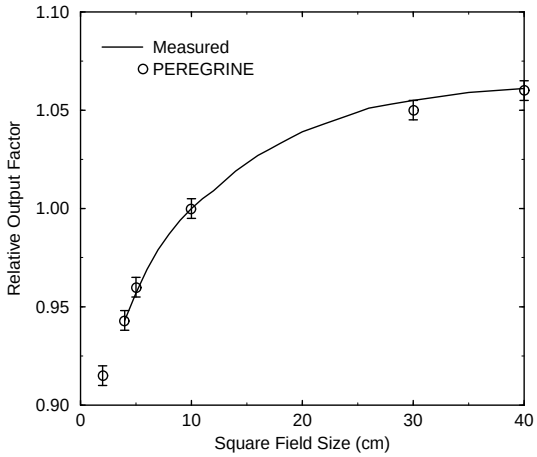

Figure 6: Square field output factors calculated by PEREGRINE vs. measured values [7] for a 6-MV Varian 600C.

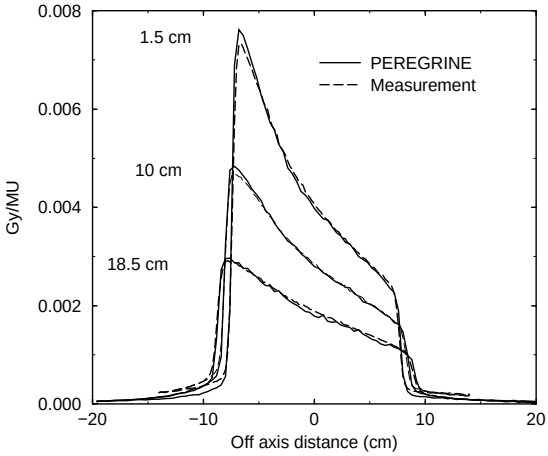

Figure 7: PEREGRINE vs. Measurement : Absolute dose comparison for 60^o lead wedge profiles (6MV) [7].

Summary

Using the techniques briefly described in this report, we are able to accurately describe various photon teletherapy sources for use in PEREGRINE for Monte Carlo dose calculations. We are actively working to extend PEREGRINE's range of beam energies and manufacturers. This source description technique allows PEREGRINE to perform accurate, absolute dose calculations in clinical configurations. The source descriptions can be adjusted to meet the configurations at individual clinics.

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